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Measurement of Time-dependent CP-Violating Asymmetries in $B^0 \to K^0_S K^0_S K^0_S$ Decays

The *BABAR* Collaboration

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We present preliminary measurements of the CP asymmetry parameters in $B^0 \to K^0_S K^0_S K^0_S$ decays, reconstructing two of the K^0_S into $\pi^+\pi^-$ and one into $\pi^0\pi^0$. In a sample of 227 M $B\overline{B}$ pairs collected by the *BABAR* detector at the PEP-II B Factory at SLAC, we find the CP parameters to be $S = \ -0.25^{+0.68}_{-0.61}(\mathrm{stat}) \pm 0.05(\mathrm{syst})$ and $C = 0.56^{+0.34}_{-0.43}(\mathrm{stat}) \pm 0.04(\mathrm{syst})$. Combining this result with the previous *BABAR* measurement, obtained from events with three K^0_S decaying into $\pi^+\pi^-$, we get

$$\begin{aligned} S &= -0.63^{+0.32}_{-0.28}\,(\mathrm{stat}) \pm 0.04(\mathrm{syst}) \\ C &= -0.10 \pm 0.25\,(\mathrm{stat}) \pm 0.05,(\mathrm{syst}) \end{aligned}$$

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1 INTRODUCTION

In the Standard Model (SM) *CP* violation arises from the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [1]. Decays of B mesons into charmless hadronic final states with three kaons are dominated by $b \to s\bar{s}s$ penguin amplitudes, while other SM amplitudes are suppressed by CKM factors [2]. Neglecting these CKM-suppressed contributions, the amplitude of time-dependent *CP* violation for these channels is proportional to $\sin 2\beta$, where $\beta = \arg(-V_{cd}V^*_{cb}/V_{td}V^*_{tb})$ is the *CP*-violating phase difference between mixing and decay amplitudes and V_{ij} are the elements of the CKM matrix. The time-dependent *CP*-asymmetry is obtained by measuring the proper time difference $\Delta t = t_{CP} - t_{\text{tag}}$ between a fully reconstructed neutral B meson (B_{CP}) in the final state $K^0_S K^0_S K^0_S$, and a partially reconstructed recoil B meson (B_{tag}). The B_{tag} decay provides evidence that it decayed either as B^0 or $\overline{B}^0$ (flavor tag). The decay rate $\mathrm{f}_+(\mathrm{f}_-)$ when the tagging meson is a $B^0(\overline{B}^0)$ is given by

$$
\begin{aligned}
\mathrm{f}_{\pm}(\Delta t) \;=\; & \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \times \\
& [\, 1 \;\pm\; S \sin(\Delta m_d \Delta t) \mp C \cos(\Delta m_d \Delta t) \,] \;,
\end{aligned}
\tag{1}
$$

where τ_{B^0} is the neutral B meson mean lifetime and Δm_d is the B^0–$\overline{B}^0$ oscillation frequency. The parameters C and S describe the magnitude of *CP* violation in the decay and in the interference between decay and mixing, respectively. The time-dependent *CP*-violating asymmetry is defined as $A_{CP} \equiv (\mathrm{f}_+ - \mathrm{f}_-)/(\mathrm{f}_+ + \mathrm{f}_-)$.

Since at first approximation $b \to s$ decays can be considered as given by a single amplitude, no direct *CP* violation is expected ($C \sim 0$) and $S \sim -\eta_f \sin 2\beta$, where C (S) is the parameter for direct (mixing-induced) *CP* violation and $\eta_f = +1(-1)$ corresponds to *CP*-even (-odd) final states. In general, a deviation from these expectations might occur without indicating the presence of physics beyond the Standard Model, since a second (CKM suppressed) part is present in the decay amplitude. The interference between these two terms can in general produce direct *CP* violation and introduce a nontrivial relation between S and $-\eta_f \sin 2\beta$, as a function of the relative phase and size of the two amplitudes. It has been noted that for $B^0 \to K^0_S K^0_S K^0_S$ (which is a $\eta_f = +1$ state), as for the golden mode $B^0 \to \phi K^0_S$, this suppressed amplitude is a penguin contribution as well [3–5], so that the ratio of the two terms is expected to be of the order of λ^2, where $\lambda = 0.2258 \pm 0.0014$ [6] is the sine of the Cabibbo angle.

The value of $\sin 2\beta = 0.726 \pm 0.037$ determined from tree-level $b \to c\bar{c}s$ decays is in good agreement with the SM expectaion [6,7]. On the other hand, $b \to s\bar{q}q$ processes are dominated by one-loop transitions, and hence may have contributions from diagrams with new heavy particles. Thus, a sizable deviation of S from $-\eta_f \sin 2\beta$ would be a signal of physics beyond the Standard Model [8].

Belle and *BABAR* Collaboration have already reported a measurement of time-dependent *CP*-asymmetry in $B^0 \to K^0_S K^0_S K^0_S$ [9]. In the case of *BABAR* the analysis includes only K^0_S decaying into $\pi^+\pi^-$. Since this measurement might be limited in precision by the amount of data one expects to have at the end of *BABAR* experiment, the present work has the main purpose of improving the precision using the same dataset, but reconstructing one of the K^0_S in the $\pi^0\pi^0$ decay mode. Because of the absence of charged tracks originating from the B^0 decay vertex, we use the vertexing technique recently developed for $B^0 \to K^0_S \pi^0$ [10].

2 THE *BABAR* DETECTOR

The *BABAR* detector is described elsewhere [11]. The components are a charged-particle tracking system consisting of a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) surrounded by a 1.5-T solenoidal magnet with an instrumented flux return (IFR), an electromagnetic calorimeter (EMC) comprised of 6580 CsI(Tl) crystals, and a detector of internally reflected Cherenkov light (DIRC) providing excellent charged $K-\pi$ separation up to a momentum of 4.5 GeV/c relevant for this analysis.

3 ANALYSIS METHOD

The $B^0 \to K^0_S K^0_S K^0_S$ candidate (B_{CP}) is reconstructed combining three K^0_S candidates, two of which are reconstructed in the $K^0_S \to \pi^+\pi^-$ mode, while the third is reconstructed in the $K^0_S \to \pi^0\pi^0$ mode. We reconstruct $K^0_S \to \pi^+\pi^-$ candidates from pairs of oppositely charged tracks. The two-track composites must form a vertex with a $\pi^+\pi^-$ invariant mass within 11 MeV/c^2 (about 4σ) of the nominal K^0_S mass [12]. We form $\pi^0 \to \gamma\gamma$ candidates from pairs of photon candidates in the EMC. Each photon is required to be isolated from any charged tracks, to carry a minimum energy of 50 MeV, and to have the expected lateral shower shape. We reconstruct $K^0_S \to \pi^0\pi^0$ candidates from π^0 pairs which form an invariant mass $480 < m_{\pi^0\pi^0} < 520\,\mathrm{MeV}/c^2$. $B^0 \to K^0_S K^0_S K^0_S$ candidates are constrained to originate from the e^+e^- interaction point using a geometric fit, based on a Kalman Filter [13]. We make a requirement on the consistency of the χ^2 of the fit which retains 93% of the signal events, and rejects about 49% of other B decays. We extract the $K^0_S \to \pi^+\pi^-$ decay length $L_{K^0_S}$ and the invariant mass ($m_{\gamma\gamma}$) from this fit, and require $100 < m_{\gamma\gamma} < 141\,\mathrm{MeV}/c^2$ and $L_{K^0_S}$ greater than 5 times its uncertainty.

For each B candidate we compute two kinematic variables, namely the invariant mass m_B and the missing mass $m_{\mathrm{miss}} = \sqrt{(q_{e^+e^-} - \tilde{q}_B)^2}$, where $q_{e^+e^-}$ is the four-momentum of the initial e^+e^- system and $\tilde{q}_B$ is the four-momentum of the $B^0 \to K^0_S K^0_S K^0_S$ candidate after a mass constraint on the B^0 is applied. By construction the linear correlation coefficient between m_{miss} and m_B vanishes. This combination of variables shows smaller correlation (0.86% on reconstructed signal Monte Carlo events and 1.64% on the final data sample) and a better background suppression with respect to the equivalent kinematic variables ΔE and m_{ES} used in the *BABAR* analysis of this mode with all $K^0_S \to \pi^+\pi^-$ in the final state [9]. Using simulations of $B^0 \to K^0_S K^0_S K^0_S$ and $B^0 \to J/\psi(\to l^+l^-)K^0_S(\to \pi^0\pi^0)$ decays ($l = e, \mu$) and reconstructing $B^0 \to J/\psi(\to l^+l^-)K^0_S(\to \pi^0\pi^0)$ events on data, we determine the distribution of m_{miss} and m_B for signal events. We find the signal resolution for m_B to be about $40\,\mathrm{MeV}/c^2$, the distribution being asymmetric around the maximum, because of leakage effects in the EMC. The signal resolution for m_{miss}, about $6\,\mathrm{MeV}/c^2$, is dominated by the beam-energy spread. We select candidates with m_B within $150\,\mathrm{MeV}/c^2$ of the nominal B^0 mass [12] and with $5.11 < m_{\mathrm{miss}} < 5.31\,\mathrm{GeV}/c^2$. The region $m_{\mathrm{miss}} < 5.2\,\mathrm{GeV}/c^2$ is devoid of signal and used for background characterization. Most background originates from continuum $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$) events, which we suppress using both production and decay properties. To exploit the jet-like topology of continuum events, we use the angle θ_T between the thrust axis of the B_{CP} candidate and the thrust axis formed from the other charged and neutral particles in the event. While $|\cos\theta_T|$ is highly peaked near 1 for $e^+e^- \to q\overline{q}$ events, it is nearly uniformly distributed for $B\overline{B}$ events. We require $|\cos\theta_T| < 0.95$. Moreover, we calculate the ratio L_2/L_0 of two angular moments defined as $L_j \equiv \sum_i |\mathbf{p}^*_i||\cos\theta^*_i|^j$, where $\mathbf{p}^*_i$ is the momentum of particle i in the e^+e^- rest frame, θ^*_i is the angle between $\mathbf{p}^*_i$ and the thrust axis of the B candidate and the sum runs over all reconstructed particles except for the B-candidate daughters. After all selection requirements are applied, the average candidate multiplicity in events with at least one candidate is approximately 1.67, coming from multiple $K^0_S \to \pi^0\pi^0$ combinations. In these cases, we select the candidate with the smallest $\chi^2 = \sum_i (m_i - m_{K^0_S})^2/\sigma^2_{m_i}$, where m_i ($m_{K^0_S}$) is the measured (nominal K^0_S) mass and σ_{m_i} is the estimated uncertainty on the mass of the ith K^0_S candidate. In simulated events, this selection criterion gives the right answer about 81% of the time. The remaining misreconstructed events, coming from fake $K^0_S \to \pi^0\pi^0$ candidates, do not affect the determination of Δt and have a small impact on the other variables used in the final fit (the largest correlation is $\sim 2.5\%$).

Events coming from $b \to c\bar{c}s$ would reduce any sensitivity to departures from the Standard Model, as this process is characterized by a Standard-Model CP asymmetry ($S \sim \sin 2\beta$ and $C \sim 0$). We therefore remove $b \to c\bar{c}s$ events by rejecting all candidates with a $K^0_S K^0_S$ mass combination within two times the experimental resolution of the χ_{c0} mass. The contribution from χ_{c2} is found to be negligible. Combinatorics from other B decays constitute a further source of background. We take this into account by adding a component in the likelihood fit (see Sec. 4), where the shape of each likelihood variable is determined from a simulation of inclusive B decays.

For each $B^0 \to K^0_S K^0_S K^0_S$ candidate we examine the remaining tracks in the event to determine the decay vertex position and the flavor of B_{tag}. Using a neural network based on kinematic and particle identification information [14] each event is assigned to one of seven mutually exclusive tagging categories, designed to combine flavor tags with similar performance and Δt resolution. We parameterize the performance of this algorithm in a data sample (B_{flav}) of fully reconstructed $B^0 \to D^{(*)-}\pi^+/\rho^+/a_1^+$ decays. The average effective tagging efficiency obtained from this sample is $Q = \sum_c \epsilon^c_S (1-2w^c)^2 = 0.299 \pm 0.005$, where ϵ^c_S and w^c are the efficiencies and mistag probabilities, respectively, for events tagged in category $c = 1, 2, \cdots 7$. For the background, the fraction of events (ϵ^c_B) and the asymmetry in the rate of B^0 versus $\overline{B}^0$ tags in each tagging category are extracted from a fit to the data.

The proper-time difference is extracted from the separation of the B_{CP} and B_{tag} decay vertices. The B_{tag} vertex is reconstructed inclusively from the remaining charged particles in the event. To reconstruct the B_{CP} vertex from the single K^0_S trajectory we exploit the knowledge of the average interaction point (IP), which is determined on a run-by-run basis from the spatial distribution of vertices from two-track events. We compute Δt and its uncertainty from a geometric fit to the $\Upsilon(4S) \to B^0\overline{B}^0$ system that takes this IP constraint into account. We further improve the sensitivity to Δt by imposing a Gaussian constraint on the sum of the two B decay times ($t_{CP}+t_{\text{tag}}$) to be equal to $2\,\tau_{B^0}$ with an uncertainty $\sqrt{2}\,\tau_{B^0}$, which effectively constrains the two vertices to be near the $\Upsilon(4S)$ line of flight [10]. We have verified in a Monte Carlo simulation that this procedure provides an unbiased estimate of Δt. Details on the vertexing algorithm can be found in Ref. [13].

The per-event estimate of the uncertainty on Δt reflects the strong dependence of the Δt resolution on the K^0_S flight direction and on the number of SVT layers traversed by the K^0_S decay daughters. In about 97% of the events at least one of the two K^0_S which decay into $\pi^+\pi^-$ have both pion tracks reconstructed from at least 4 SVT hits, leading to sufficient resolution for the time-dependent measurement. The average Δt resolution in these events is about 1.0 ps. For events which fail this criterion or for which $\sigma(\Delta t) > 2.5$ ps or $\Delta t > 20$ ps, the Δt information is not used. However, since C can also be extracted from flavor tagging information alone, these events still contribute to the measurement of C.

4 MAXIMUM LIKELIHOOD FIT

We extract the results from unbinned maximum-likelihood fits to the kinematic, event shape L_2/L_0, Δt, and flavor tag variables. We maximize the logarithm of an extended likelihood function

$$\begin{aligned}\mathcal{L}(S, C, N_S, N_B, N_{B\bar{B}} f_S, f_B, f_{B\bar{B}}, \vec{\alpha}) \;=\; & e^{-(N_S+N_B+N_{B\bar{B}})} \times \\ \prod_{i\in I} & \left[N_S f_S \epsilon_S^c \mathcal{P}_S(\vec{x}_i, \vec{y}_i; S, C) + N_B f_B \epsilon_B^c \mathcal{P}_B(\vec{x}_i, \vec{y}_i; \vec{\alpha}) + N_{B\overline{B}} f_{B\overline{B}} \epsilon_{B\overline{B}}^c \mathcal{P}_{B\overline{B}}(\vec{x}_i, \vec{y}_i; \vec{\alpha})\right] \times \\ \prod_{i\in II} & \left[N_S(1-f_S)\epsilon_S^c \mathcal{P}'_S(\vec{x}_i; C) + N_B(1-f_B)\epsilon_B^c \mathcal{P}'_B(\vec{x}_i; \vec{\alpha}) + N_{B\overline{B}}(1-f_{B\overline{B}})\epsilon_{B\overline{B}}^c \mathcal{P}'_{B\overline{B}}(\vec{x}_i; \vec{\alpha})\right],\end{aligned} \qquad (2)$$

where I (II) is the subset of events with (without) Δt information. The N_X (X being signal, continuum background, or $B\overline{B}$ background) represent the X component yield, and f_X the fraction of events with Δt information. The probabilities $\mathcal{P}_X$ ($\mathcal{P}'_X$) are products of PDFs for each X hypotheses, evaluated for each event i from the values of $\vec{x}_i = \{m_B, m_{\text{miss}}, L_2/L_0, \text{tag}, \text{tagging category}\}$ and $\vec{y}_i = \{\Delta t, \sigma_{\Delta t}\}$. The remaining parameters of the fit are denoted by $\vec{a}$. For the B background events, the efficiencies and the mistag probabilities $\epsilon_{B\bar{B}}^c$ and w^c, respectively, for the tagging category c, are fixed to the same values of the signal events. The observables are sufficiently uncorrelated that we can construct the likelihoods as the products of one-dimensional PDFs. The PDFs for signal are parameterized from simulations of signal events. For background PDFs we determine the functional form from data in the sideband regions of the other observables where backgrounds dominate. We include these regions in the fitted sample and simultaneously extract the parameters of the background PDFs along with the fit results. All the parameters of $B\overline{B}$ background PDFs are determined using simulated samples of inclusive B decays. All the parameters of the likelihood that are not determined simultaneously with S and C in the final fit are varied according to their uncertainties in order to estimate systematic errors.

The average Δz resolution is dominated by the tagging vertex in the event. Thus, we can characterize the resolution with a much larger sample of reconstructed $B \to DX$ decays (B_{flav} sample), which we use as signal parameterization. The amplitudes for the B_{CP} asymmetries and for the B_{flav} flavor oscillations are reduced by the same factor due to wrong tags. Both distributions are convoluted with a common Δt resolution function (RF). The RF is parameterized as the sum of two Gaussians with a width proportional to the reconstructed $\sigma_{\Delta t}$, and a third Gaussian with a fixed width of 8 ps, which accounts for a small fraction of outlying events [14]. The first two Gaussians have a non-zero mean, proportional to $\sigma_{\Delta t}$, to account for the small bias in Δt from charm decays on the B_{tag} side. Backgrounds are accounted for by adding terms to the likelihood, incorporated with different assumptions about their Δt evolution and resolution function.

The fit procedure was tested with both a parameterized simulation of a large number of data-sized experiments and a full detector simulation. The likelihood of our data fit agrees with the likelihoods from fits to the simulated data.

5 SYSTEMATIC STUDIES

We obtain systematic uncertainties in the CP coefficients S and C due to the parameterization of PDFs for the event yield in signal and background by varying the parameters within one standard deviation (evaluated from a fit to Monte Carlo simulated events). We evaluate the uncertainties associated with the assumed parameterization of the Δt resolution function for signal and $B\overline{B}$-background, a possible difference in the efficiency between B^0 and $\overline{B}^0$, and the fixed values for

Δm_d and τ_{B^0} by varying the parameters within one standard deviation (extracted from a fit to the B_{flav} sample). The sum of the two contributions gives the total error associated with the PDF parameters. We estimate different uncertainties associated with vertexing. The first is obtained by taking the largest value of $S(C)_{\text{fit}} - S(C)_{\text{true}}$ from fits to signal Monte Carlo events. Here the $S(C)_{\text{fit}}$ represents the result of the fit to our signal Monte Carlo sample, while $S(C)_{\text{true}}$ represents input values in the Monte Carlo generation. The second uncertainty is from possible SVT layers misalignment. We assign a systematic uncertainty on our knowledge of the beam spot position by shifting the beam position in the simulation by $\pm 20\ \mu m$ in the vertical direction. The sensitivity due to any calibration problems or time-dependent effects is evaluated by smearing the beam-spot position by an additional $\pm 20 \mu m$ in the vertical direction. We include an additional contribution from the comparison of the description of the RF between BC vertexing and nominal vertexing in the case of $B^0 \to J/\psi K^0_S$ events. We estimate also the errors due to the effect of doubly CKM-suppressed decays on the tag side [15]. We add these contributions in quadrature to obtain the total systematic uncertainty. The summary is reported in Table 1. The largest contribution is related to the knowledge of the PDF parameters. For reference, we note that this effect produces a systematic error of ± 1.7 events on the signal yield.

	$\Delta\ S(+)$	$\Delta\ S(-)$	$\Delta\ C(+)$	$\Delta\ C(-)$
PDF parameters	0.046	0.039	0.029	0.027
vertexing method	0.012	0.012	0.025	0.025
SVT alignment	0.004	0.004	0.008	0.008
beam-spot	0.003	0.003	0.005	0.005
data/MC RF	0.006	0.006	0.001	0.001
doubly-CKM-suppressed decays	0.001	0.001	0.011	0.011
total errors	0.049	0.041	0.041	0.039

Table 1: Summary of systematic uncertainties on S and C.

6 SUMMARY OF RESULTS

In the final sample composed of 2748 B candidates we measure $41.0^{+9.2}_{-8.3}$ signal events, 2700 ± 56 continuum background events and 7^{+24}_{-19} $B\overline{B}$-background events. Assuming the world average for the branching ratio $((6.2 \pm 0.9) 10^{-6})$ [9] and the reconstruction efficiency as estimated from a sample of simulated signal events, we expected 45 ± 7 events, which is in good agreement with the result. We find this preliminary result on *CP* parameters:

$$
\begin{aligned}
S &= -0.25^{+0.68}_{-0.61}(\text{stat}) \pm 0.05(\text{syst}) \\
C &= 0.56^{+0.34}_{-0.43}(\text{stat}) \pm 0.04(\text{syst}).
\end{aligned}
$$

Fig. 1 shows the background-subtracted distributions of m_{miss} and m_B for these events, obtained using the sPlot weighting technique [16]. Events contribute according to a weight constructed from the covariance matrix for the yields (N_S and N_B) and the probability $\mathcal{P}_S$ and $\mathcal{P}_B$ for the event, computed without the use of the variable that is being displayed. The curves represent the signal PDFs used in the fit. We combined this result with the previous *BABAR* measurement, obtained using $B^0 \to K^0_S K^0_S K^0_S$ reconstructed from all three K^0_S decaying into $\pi^+\pi^-$ [9]. The combination is

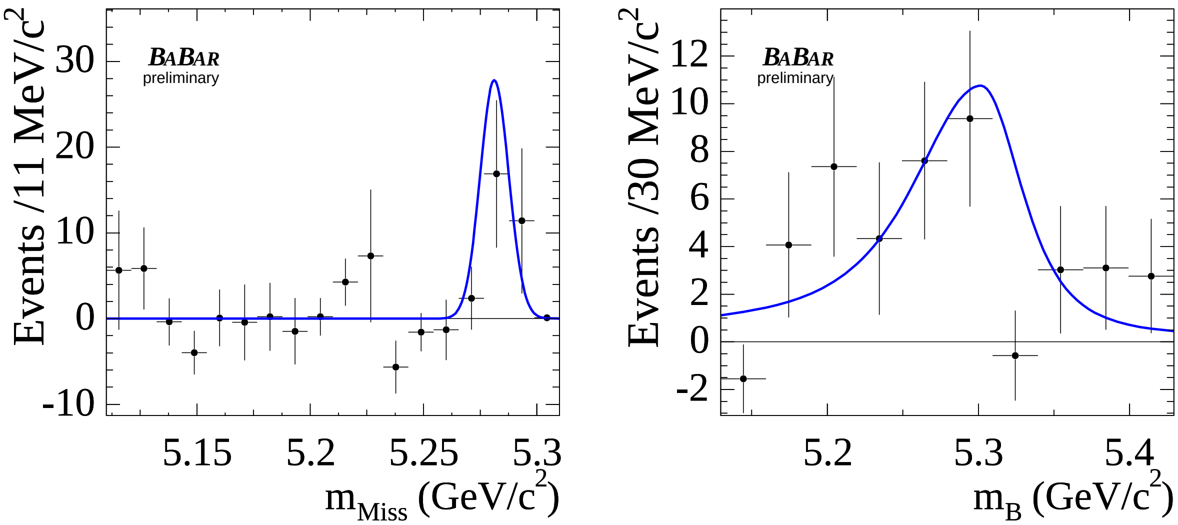

Figure 1: Distribution of the event variable $m_{\rm miss}$ (left) and m_B after reconstruction with the weighting technique described in the text.

obtained through a simultaneous maximum likelihood fit, which takes into account the correlations from the common Δt PDF. The total systematic error is calculated by summing in quadrature the uncorrelated sources of errors and taking the largest contribution from the two analyses in the case of common sources of background. In this way, we obtain this preliminary result:

$$
\begin{aligned}
S &= -0.63^{+0.32}_{-0.28}\,(\text{stat}) \pm 0.04(\text{syst}) \\
C &= -0.10 \pm 0.25\,(\text{stat}) \pm 0.05, (\text{syst})
\end{aligned}
$$

In Fig. 2 we show the distributions of signal events, obtained using the sPlot weighting technique [16], in the case of $B^0 \to K^0_S K^0_S K^0_S$ with one K^0_S reconstructed by $\pi^0\pi^0$ mode (left) and for the combined fit (right). The superimposed curves represent the results of the fit in the two cases.

Considering the present uncertainty, this result agrees with Standard Model expectations. A future update of this analysis, including new data collected by *BABAR*, will help to understand if the present hint of pattern in the deviation of $b \to s$ penguins from the Standard Model predictions [17] is a statistical effect or a signal of new physics.

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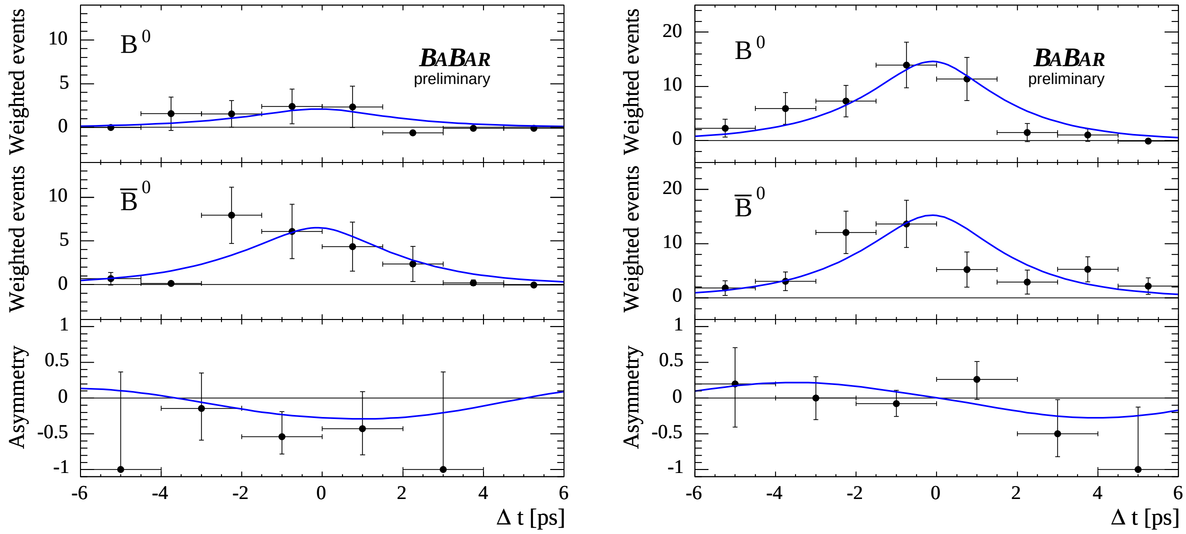

Figure 2: Distributions of Δt for weighted events with $B_{\rm tag}$ tagged as B^0 (upper plots) or $\overline{B}^0$ (middle plots), and the asymmetry (lower plots). Left plots are for the subsample with all $K_S^0 \to \pi^0\pi^0$, right plots are for the combined fit. The points are weighted data and the curves are the PDF projections.

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We present preliminary measurements of the CP asymmetry parameters in $B^0 \to K^0_S K^0_S K^0_S$ decays, reconstructing two of the K^0_S into $\pi^+\pi^-$ and one into $\pi^0\pi^0$. In a sample of 227 M $B\bar{B}$ pairs collected by the BABAR detector at the PEP-II B-Factory at SLAC, we find the CP parameters to be $S = -0.25^{+0.68}_{-0.61}(\mathrm{stat}) \pm 0.05(\mathrm{syst})$ and $C = 0.56^{+0.34}_{-0.43}(\mathrm{stat}) \pm 0.04(\mathrm{syst})$. Combining this result with the previous BABAR measurement, obtained from events with three K^0_S decaying into $\pi^+\pi^-$, we get

$$
\begin{aligned}
S &= -0.63^{+0.32}_{-0.28}\,(\mathrm{stat}) \pm 0.04(\mathrm{syst}) \\
C &= -0.10 \pm 0.25\,(\mathrm{stat}) \pm 0.05(\mathrm{syst})
\end{aligned}
$$